

## Attachment 1

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Motion Model Development  
for  
Very Shallow Water/Surf Zone Crawler (U)

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#### ABSTRACT

The Very Shallow Water/Surf Zone (VSW/SZ) environment presents a challenging problem to Mine Countermeasures (MCM) operations conducted in military operations involving amphibious landings. Present tactics involve human swimmers and present a risky and time-consuming scenario.

There are Unmanned Autonomous Vehicle (UAV) systems under development that will replace the human swimmers in VSW/SZ MCM operations. One of these systems is an Unmanned Ground Vehicle (UGV), commonly known as a crawler. The crawler system is a small tracked vehicle, which will carry a suite of sensors that will enable it to perform necessary MCM functions such as detect, classify, identify, mark, re-acquire, and neutralize threat targets.

To aid in the development of the crawler system and associated tactical use, a three degree-of-freedom motion model is being developed for incorporation into an engineering level simulation under development at the Coastal Systems Station (CSS). At present the equations of motion with empirical force models have been implemented into the simulation.

#### INTRODUCTION

Mine Countermeasures (MCM) operations in the Very Shallow Water/Surf Zone (VSW/SZ) present special problems over and above those encountered in deeper water operations. The VSW and SZ regions are defined as 12.2 meters (40 feet) to 3.1 meters (10 feet) and 3.1 meters to 0 meters water depth respectively. At these depths factors such as water and bottom boundaries, air bubbles, particulate matter, surf action, etc., will make more difficult, as contrasted with deeper water, the motion of vehicles and the propagation of information carrying signals.

In addition to the more difficult physics based problems in the VSW/SZ environment, MCM operations, at present, require the use of human swimmers. The detect, classify, identify, mark, re-acquire and neutralize MCM functions present a high risk factor to safety. Several concepts attempt to reduce this risk by the use of special designed vehicles to carry out the required MCM functions. One of these is a small tracked vehicle carrying a suite of sensors designed to perform the MCM operations in the VSW/SZ environment. This vehicle, commonly called a crawler, will be designed to operate autonomously in this environment.

A number of problems in the development of the crawler system involve complex issues, which can be solved more readily using physics based simulation analysis. One of the basic problems is to describe the motion of the crawler as it moves on the sea bottom in the VSW/SZ region under the influence of a number of different forces. These forces, consisting of gravity, ocean currents, wave action, drag, buoyant, and soil interactions, can affect the crawler motion on the sea bottom. This resulting motion will determine platform orientation and can result in a degradation of the MCM capability of the sensor suite as well as the amount of time needed to cover the designated sea bottom search area.

To study the problems a crawler will encounter in the VSW/SZ environment and to assist in system design, a three degree-of-freedom (3DOF) planar motion model is under development at the Coastal Systems Station (CSS). The basic equations of motion and an empirical resistive force model have been developed and implemented into an engineering level simulation system also under development at CSS. This engineering level simulation, the Autonomous Littoral Warfare Systems Evaluator-Engineering Simulation (ALWSE-ES), will include models of crawlers, hydrodynamic vehicles, sea bottom terrain, and environmental parameters of the water column, water surface and sea bottom. At present an operator input for independent right and left tracks tractive forces along with gravity force resolved along the body axes are used. A model that computes the forces due to wave action has been developed but not implemented in the simulation. The crawler model uses the existing bottom terrain data and visualization capabilities in ALWSE-ES.

Current efforts for the crawler model involve developing the functional forms of the models for tractive, resistive, drag, and buoyant forces. Future work will involve measurements of the physical parameters required for the functional force models and the verification of these models.

## MODEL DEVELOPMENT

In this paper these conventions will be used:

$X, Y, Z$	Fixed coordinate system axes
$x, y, z$	Body coordinate system axes
$\phi$	Euler angle of rotation (roll) about the X-axis
$\theta$	Euler angle of rotation (pitch) about the Y-axis
$\psi$	Euler angle of rotation (yaw) about the Z-axis
$\dot{\phi}, \dot{\psi}, \dot{\theta}$	Angular velocity components about the fixed coordinate system axes
$\dot{X}, \dot{Y}, \dot{Z}$	Velocity components along X, Y, Z-axes, respectively
$u, v, w$	Velocity components along x, y, z-axes, respectively
$\dot{u}, \dot{v}, \dot{w}$	Acceleration components along x, y, z-axes, respectively
$p, q, r$	Angular velocities (roll, pitch, yaw) about x, y, z-axes, respectively
$\dot{p}, \dot{q}, \dot{r}$	Angular acceleration components about x, y, z-axes, respectively

$F_x, F_y, F_z$	Total external forces along x, y, z-axes, respectively
$K, M, N$	Total external torques along x, y, z-axes, respectively
$F$	Total external force vector acting on the crawler
$N$	Total external torque vector acting on the crawler
$a$	Total acceleration vector acting on the crawler
$L$	Total angular momentum vector on the crawler
$M$	Mass of the crawler
$\omega$	Total angular velocity vector of the crawler
$\{I\}$	Total inertia tensor of the crawler
$I_x, I_y, I_z$	Moments of inertia of the crawler about the x, y, z-axes, respectively
$I_{xy}, I_{xz}, \text{ etc.}$	Products of inertia of the crawler

A bold character represents a vector, a dot above a character represents the time derivative and the symbol around a bold character represents a tensor. Right hand coordinate systems are used with right hand rotations, i.e. x into y represents a rotation about the z-axis, y into z a rotation about x, and z into x a rotation about y. A fixed coordinate system with the origin at some arbitrary point on the sea surface, the Z-axis pointing down, and the X-axis pointing toward North is used. The crawler body system has the x-axis along the longitudinal axis and exits out the front of the vehicle, the y-axis out the right side, and z points down out of the crawler bottom.

### EQUATIONS OF MOTION

The coordinate systems used for the equations of motion development are shown in Figure 1. If one begins with Newton's laws of motion and considers a rigid body with the origin of the body coordinate system located at the center of gravity of the crawler, the equations

$$\mathbf{F} = m\mathbf{a} \quad (1)$$

$$\mathbf{N} = d\mathbf{L}/dt = d(\{I\} \cdot \boldsymbol{\omega})/dt \quad (2)$$

can be expanded to obtain the general, non-linear, coupled differential equations of motion <sup>1,2,3</sup>

$$F_x = m(\dot{u} - vr + wq) \quad (3)$$

$$F_y = m(\dot{v} - wp + ur) \quad (4)$$

$$F_z = m(\dot{w} - uq + vp) \quad (5)$$

$$K = I_x \dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} \quad (6)$$

$$M = I_y \dot{q} + (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz} \quad (7)$$

$$N = I_z \dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx} \quad (8)$$

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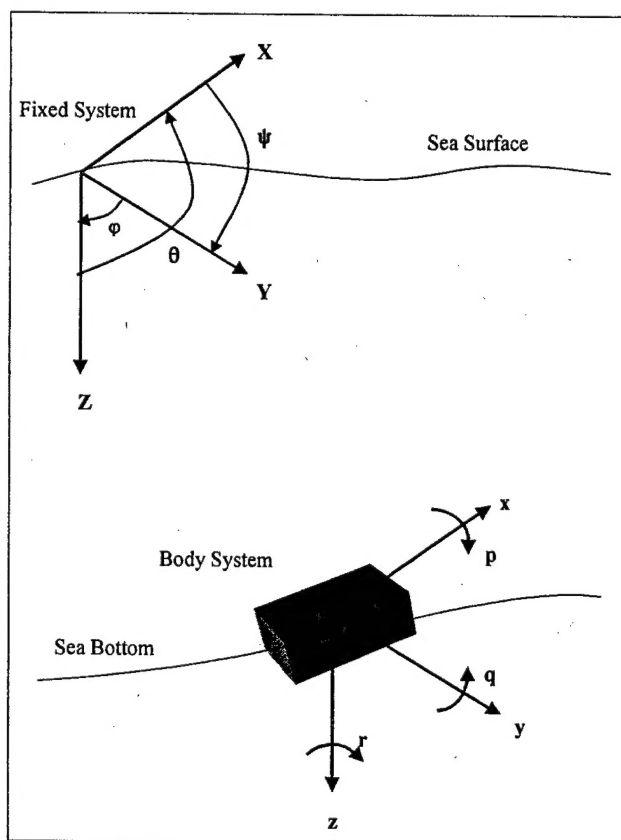


FIGURE 1. COORDINATE SYSTEMS

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These equations define a body with six degrees of freedom, three for spatial location and three for orientation. This 6 degree of freedom (6DOF) set of equations has  $x$ ,  $y$ , and  $z$  for spatial coordinates and  $p$ ,  $q$ , and  $r$  for angular velocities.

A planar motion or 3DOF has been assumed for the crawler since it is constrained to follow the sea bottom terrain. The degrees of freedom are  $x$ ,  $y$ , and yaw. It is recognized that if a force, such as wave force, causes the crawler to leave the sea bottom and tumble, the motion will become a 6DOF problem. If this becomes a significant problem in the design or tactical use of the crawlers the full 6DOF motion will have to be implemented. This will necessitate further study of the forces acting on the crawler body since it would then be considered a swimmer.

In 3DOF or planar motion the following terms will be zero:

$$z = \dot{w} = p = q = \dot{p} = \dot{q} = 0 \quad (9)$$

Applying Equation (9) to Equations (3), (4), (5), (6), (7), and (8) leads to the set of equations

$$F_x = m (\dot{u} - vr) \quad (10)$$

$$F_y = m (\dot{v} + ur) \quad (11)$$

$$K = -\dot{r} I_{xz} + r^2 I_{yz} \quad (12)$$

$$M = -r^2 I_{zx} - \dot{r} I_{yz} \quad (13)$$

$$N = I_z \dot{r}. \quad (14)$$

This set of equations completely defines planar or 3DOF motion with the body coordinate system located at the CG of the body.

If it is assumed that the crawler's mass distribution is uniform, and the body coordinate system is located along the principal axes of inertia, the products of inertia will equal to zero or

$$I_{xz} = I_{yz}, \text{ etc.} = 0 \quad (15)$$

Applying Equation (15) to the 3DOF set of equations eliminates Equations (12) and (13) and yields the set of equations with the products of inertia equal to zero:

$$F_x = m (\dot{u} - vr) \quad (16)$$

$$F_y = m (\dot{v} + ur) \quad (17)$$

$$N = I_z \dot{r}. \quad (18)$$

It should be noted, however, that if the crawler's mass is not uniform (e.g. a heavy object is attached on one side) the products of inertia can be significant and cause a roll or pitch moment about the x or y axes. This motion could cause the crawler to have a tendency for one track to lift off the sea bottom at high yaw rates. If this becomes a problem in the crawler design the Equations (12) and (13) will be needed as well as Equations (16), (17), and (18).

The Equations (16), (17), and (18) are used in the model that is implemented in ALWSE-ES. They are solved using a Runge-Kutta numerical integration technique to start the process and a modified Hamming method to continue the solution. The solutions to Equations (16), (17), and (18) are  $u$ ,  $v$ , and  $r$  which are defined in body coordinates. These values are transformed to the fixed system using a coordinate transformation employing Euler angles that define the body system relative to the fixed system. The values in the fixed system generated by the transformation are  $\dot{X}$ ,  $\dot{Y}$ ,  $\dot{Z}$ , and  $\dot{\psi}$ . These values are integrated once with respect to time to yield  $X$ ,  $Y$ ,  $Z$ , and  $\psi$  in the fixed system. The crawler is then located uniquely in the fixed system.

### TRANSFORMATION MATRIX

The transformation of the body system values to the fixed system is given by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_F = [R] \begin{bmatrix} x \\ y \\ z \end{bmatrix}_b \quad (19)$$

where  $X, Y, Z$  are the values of a column matrix representing either position coordinates or velocity components in the fixed system and  $x, y, z$  are the values of a column matrix representing either position coordinates or velocity components in the body system. The rotation matrix,  $[R]$ , contains expressions of sines and cosines of the Euler angles of rotation,  $\phi, \theta$ , and  $\psi$  and represents a specific sequence of rotations, e.g.,  $\psi, \theta$ , and  $\phi$ .

A problem arises in obtaining the Euler angle transformation matrix. The equations of motion, Equations (16), (17), and (18), give the solutions in body space where the crawler is constrained to a plane, namely, the x-y plane and has only a yaw rotation,  $r$ . A method is therefore needed to obtain the pitch and roll Euler angles of the plane in fixed space.

The crawler solution plane in reality is a specified portion of the sea bottom or terrain facet. These facets are defined in the ALWSE-ES by three points in fixed space. The facet plane will therefore define the pitch and roll Euler angles of the body coordinate system relative to the fixed system. Therefore, in order to define the transformation matrix needed to transform the body solutions,  $u, v$ , and  $r$ , into the fixed space, the Euler angles of pitch and roll will have to be computed from the facet orientation in fixed space. The geometry used to compute the Euler angles for pitch and roll is shown in Figure 2.

Examining Equation (19), it is noticed that the rotation matrix contains expressions that are functions of the pitch and roll angles. If the values in the position column matrices for the fixed and body system can be defined, the expressions in the rotation matrix can be solved for the pitch and roll angles.

Referring to Figure 2 the vectors  $\mathbf{AB}$  and  $\mathbf{AC}$  are computed and the cross product between the two is obtained. The resulting vector is normalized which gives the unit normal vector  $\mathbf{n}$  in fixed space for the facet. This provides the input to the fixed system column matrix. The spatial coordinates for the body system are obtained by realizing that the unit normal vector for the body system has the value of  $(0, 0, -1)$ . If Equation (19), with these values of the normal vectors and using a standard sequence of rotations (yaw, pitch, and roll) is expanded, the results are non-linear equations containing sines and cosines of the yaw, pitch, and roll angles. These are difficult to solve explicitly for  $\theta$  and  $\phi$ , however, if the Euler angle,  $\psi$ , could be set to zero the solution for  $\theta$  and  $\phi$  would be much easier. A change of rotation sequence, where  $\psi$  is the last rotation, would make it possible to correctly set the value of  $\psi$  to zero. A pitch, roll, and yaw sequence was therefore used. This is permissible since to place the crawler on the facet requires only pitch and roll angles. The yaw angle is not needed to place the crawler on the facet since the equation of motion, Equation (18), gives this value.



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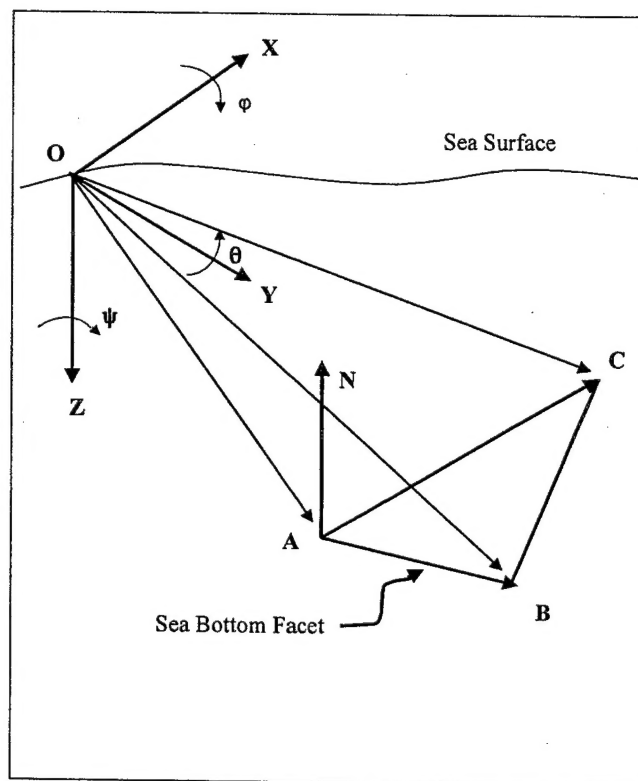


FIGURE 2. FACET GEOMETRY FOR PITCH AND ROLL ANGLES

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Therefore, using the sequence of rotations pitch, roll, yaw for the body to fixed transformation matrix leads to the rotation matrix

$$[R] = \begin{bmatrix} s\theta s\varphi s\psi & s\theta s\varphi c\psi & s\theta c\varphi \\ +c\psi c\theta & -s\psi c\theta & \\ c\varphi s\psi & c\varphi c\psi & -s\varphi \\ c\theta s\varphi s\psi & c\theta s\varphi c\psi & c\theta c\varphi \\ -c\psi s\theta & +s\psi s\theta & \end{bmatrix} \quad (20)$$

where  $s = \text{sine}$  and  $c = \text{cosine}$ . Setting yaw to zero in Equation (20) yields



$$[R]_{\psi=0} = \begin{bmatrix} c\theta & s\theta s\phi & s\theta c\phi \\ 0 & c\phi & -s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix}. \quad (21)$$

Solving Equation (19) using the components of the unit normal vector in fixed space, the unit normal in body space, and the rotation matrix given in Equation (21) yields these equations,

$$n_x = -\sin \theta \cos \phi \quad (22)$$

$$n_y = \sin \phi \quad (23)$$

$$n_z = -\cos \theta \cos \phi, \quad (24)$$

where  $n_x$ ,  $n_y$ , and  $n_z$  are the components in fixed space of the unit normal to the facet. Solving Equations (22), (23), and (24) yields the Euler angles, pitch and roll, for the facet in terms of the components of the unit normal

$$\theta = \arctan \left( \frac{-n_x}{-n_z} \right) \quad (25)$$

$$\phi = \arcsin (n_y) \quad (26)$$

To obtain the yaw value, a rotating coordinate system and a fixed system concept is used.<sup>2</sup> The angular velocity vector in terms of the Euler angles and their time derivatives is used to obtain the relationships between the body and fixed angular velocity components. Using a pitch, roll, yaw sequence, the relationships are given as:

$$\dot{\psi} = r + \left( \frac{1}{\cos(\phi)} \right) (p \sin(\psi) + q \cos(\psi)) \quad (27)$$

$$\dot{\theta} = \left( \frac{1}{\cos(\phi)} \right) (p \sin(\psi) + q \cos(\psi)) \quad (28)$$

$$\dot{\phi} = p \cos(\theta) - q \sin(\psi). \quad (29)$$

But for planar motion,  $p$  and  $q$  equal zero, therefore Equations (27), (28), and (29) reduce to

$$\dot{\psi} = r. \quad (30)$$

Equation (30) shows that for the rotation sequence of pitch, roll, and yaw, the body and fixed yaw rates are the same. Now using Equations (25), (26), and (30) the values of the Euler angles for the rotation matrix,  $[R]$ , with a pitch, roll, and yaw sequence can be obtained.

### FORCE MODELS

The forces that act on the crawler in the surf zone will include tractive, resistive, wave, hydrodynamic drag, hydrodynamic buoyant, and gravity. In this model all the forces are assumed to act upon the center of gravity (CG) except the tractive and resistive forces. In theory there will be torques due to wave and hydrodynamic drag and buoyant forces acting at points off the CG of the crawler body. Initially, however, these torques will be assumed to be small compared to the tractive and resistive components and will be ignored. Also because of the relatively slow speed of the crawler through the water and the small size, the drag and buoyant forces acting at the CG will be small and initially will be ignored.

A view of the coordinate system used to define the forces and torques acting on the crawler body is shown in Figure 3. As stated previously, all the forces are considered to act on

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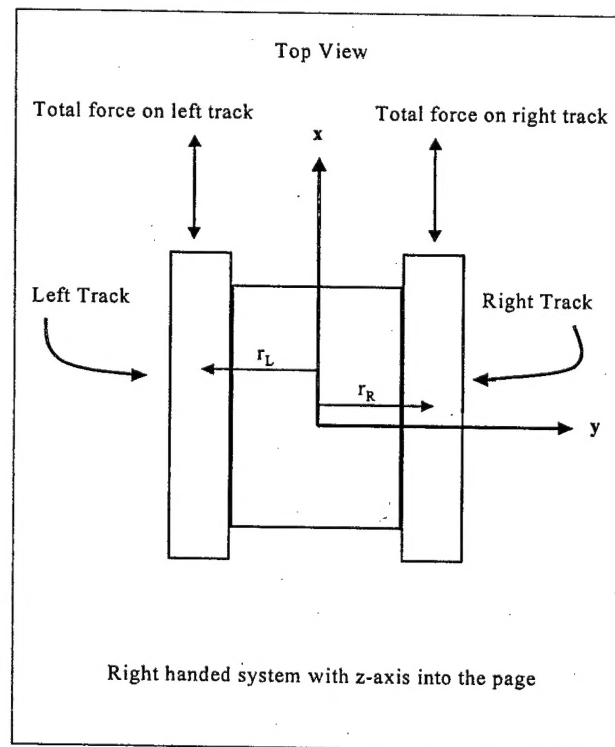


FIGURE 3. TORQUE DEFINITION

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the CG except the tractive and resistive. These forces have independent left and right crawler track components and act only along the x-axis. They are given by

$$F_{xL} = F_{xLt} + F_{xLr} \quad (31)$$

$$F_{xR} = F_{xRt} + F_{xRr} \quad (32)$$

where  $F_{xL}$  and  $F_{xR}$  are the total forces on the left and right tracks in the x-direction, respectively,  $F_{xLt}$  and  $F_{xRt}$  the left and right tractive forces, and  $F_{xLr}$  and  $F_{xRr}$  the left and right resistive forces. The total force acting on the CG along the x-axis is then given by

$$F_x = F_{xL} + F_{xR} + F_{xg} + F_{xb} + F_{xd} + F_{xw} \quad (33)$$

where  $F_{xg}$ ,  $F_{xb}$ ,  $F_{xd}$ , and  $F_{xw}$  are the x-components of gravity, buoyant, drag, and wave forces respectively.

Similarly the total forces along the y and z-axes are given as

$$F_y = F_{yg} + F_{yb} + F_{yd} + F_{yw} \quad (34)$$

$$F_z = F_{zg} + F_{zb} + F_{zd} + F_{zw} \quad (35)$$

Equations (33) and (34) are inputs to Equations (16) and (17) respectively. Equation (35) is used to determine the normal force acting on the crawler and will be an input into the physics based models for tractive and resistive forces.

At present only the functional form for the gravity force is defined. This is simply a decomposition of the gravity force in fixed coordinates into the body axes using the inverse of the transformation matrix Equation (20). A wave force model has been developed but not implemented into the motion model. The drag and buoyant functional forms are known and will be added later. The tractive forces at present are simply input as independent numbers for the left and right tracks. An empirical resistive force model given by an equation of the form

$$F_{xLr} = -C1 \text{ sign}(u) - C2 u \quad (36)$$

is being used at present. The constants  $C1$  and  $C2$  are adjusted to give the crawler a realistic time to achieve maximum speed and realistic time to slow from maximum speed to complete stop. Independent resistive forces for both the x and y directions are used. An equation similar to Equation (36) where  $u$  is replaced by  $r$  is used for the yaw motion.

Future work will make use of References 4, 5, and 6 to obtain realistic functional forms of the tractive and resistive forces. It is expected that physical measurements of the soil/track interactions will be necessary since the references cited deal mainly with large tracked vehicles such as heavy tractors, tanks, etc.

## TORQUE MODEL

Referring to Figure 3, the torque is defined as total torque due to tractive and resistive forces on left track and right tracks. The basic definition of torque,  $N = r \times F$  is applied to arrive at a torque due to left track forces and right track forces or

$$N_L = r_L \times (F_{xLt} + F_{xLr}) \quad (37)$$

$$N_R = r_R \times (F_{xRt} + F_{xRr}). \quad (38)$$

The total torque that is input into Equation (18) is then given by

$$N = N_L + N_R \quad (39)$$

### SIMULATION OPERATION

The ALWSE-ES simulation can be considered to have an executive program that essentially does bookkeeping chores such as updating state vectors of all the objects, and driving visualization and data collection programs. For the necessary input data to accomplish these tasks, it branches to specialized physics-based models, such as the crawler motion model.

The order of operation, then, is the ALWSE-ES executive branches to the motion model that computes the  $u$ ,  $v$ , and  $r$  values in body space using Equations (16), (17), and (18). These values along with values of  $\psi$ ,  $\theta$ , and  $\phi$  from the state vector for the crawler in the fixed system

$$S = f(X, Y, Z, \dot{X}, \dot{Y}, \dot{Z}, \psi, \theta, \phi, \dot{\psi}, \dot{\theta}, \dot{\phi}) \quad (40)$$

are used in Equation (19) to compute the crawler velocities  $\dot{X}, \dot{Y}, \dot{Z}$  in fixed space. Equation (30) is used to obtain the crawler angular velocity  $\dot{\psi}$  in fixed space. These values are integrated once with respect to time to obtain the crawler position coordinates,  $X$ ,  $Y$ , and  $Z$  and Euler yaw angle  $\psi$  in fixed space. The ALWSE-ES executive then obtains, from the new fixed position coordinates, the particular sea bottom terrain facet on which it is located. The normal in fixed space is computed, as outlined in Figure 2, and the new Euler angles  $\theta$  and  $\phi$  in fixed space are computed. These new values of fixed position coordinates and Euler angles are used to update the state vector and the process is repeated for a new time step.

### SUMMARY

The crawler motion has been implemented into the ALWSE-ES simulation using a 3DOF model. Place-holder force models with the exception of an empirical resistive model are being used. A wave force model has been developed and will be implemented in the near-time frame. Future work will develop the physics-based models for tractive, drag, and buoyant forces.

Although a 3DOF model is being used with the products of inertia equal to zero, the full 6DOF model with the complete inertia can be implemented, if needed, in a minimal amount of time. The existing 3DOF capability, however, is believed to be sufficient to study the majority of problems in the crawler design or operation with a sensor suite.

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hints during our discussions of vehicle dynamics certainly shortened the time of the model development. In addition, he developed the wave force model that will be used. Mr. Matson was responsible for the numerical integration program used to solve the equations of motion. Mr. Gilman's knowledge of the ALWSE-ES simulation made the task of developing a motion model compatible with ALWSE-ES much easier. Without these individual's contributions, the model development would certainly have taken longer.

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